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AlN/GaN heterostructures offer the highest possible 2D electron gas concentration with reasonable mobility while the thinnest possible barrier in single heterostructure based HEMTs. As a result, they are very attractive for ultra-scaled high-speed GaN transistors (ft/fmax > 300 GHz). Indeed our group was the first to demonstrate promising results of AlN/GaN HEMTs: Idmax of 2.3 A/mm, gm,ext of 480 S/mm and gm,int of > 1 S/mm, and extrinsic ft/fmax of 52/60 GHz. [Zimmermann 2008 IEEE EDL] However, it has been challenging to harvest these properties due to ohmic contact formation, gate leakage and lack of effective back barriers. In this program we focused on the following tasks and achievements. The research findings have been partly documented in three Ph.D. dissertations [Yu Cao 2010, David Deen 2011 and Tian Fang 2012], 11 journal publications and 3 conference papers, which are listed below.

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# Air Force Office of Scientific Research

## Final Technical Report on

## Stacked Quantum Wire AlN/GaN HEMTs

(FA9550-09-1-0198)

March, 2009 to November 30, 2011

By Huili (Grace) Xing and Debdeep Jena

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**Project overview:** AlN/GaN heterostructures offer the highest possible 2D electron gas concentration with reasonable mobility while the thinnest possible barrier in single heterostructure based HEMTs. As a result, they are very attractive for ultra-scaled high-speed GaN transistors ($f_t/f_{max}$ > 300 GHz). Indeed our group was the first to demonstrate promising results of AlN/GaN HEMTs: $I_{dmax}$ of 2.3 A/mm, $g_{m,ext}$ of 480 S/mm and $g_{m,int}$ of > 1 S/mm, and extrinsic $f_t/f_{max}$ of 52/60 GHz. [Zimmermann 2008 IEEE EDL] However, it has been challenging to harvest these properties due to ohmic contact formation, gate leakage and lack of effective back barriers. In this program we focused on the following tasks and achievements.

A. Successful development of an ohmic regrowth process by MBE to achieve a contact resistance from metal to the 2DEG $R_c$ < 0.1 ohm-mm in GaN HEMTs.

   Future direction: to improve this process in AlN/GaN/AlN quantum well HEMTs.

B. MBE growth studies of AlN/GaN/AlN multiple heterostructures to achieve sharp interfaces, confirmed by both structural and electrical characterizations.

   Future direction: to understand limiting factors of the currently observed low electron mobility < 1000 cm$^2$/Vs.

C. Study of interface property between ALD oxides and AlN/GaN and observation of interface charge most likely coupled with polarization charge in the heterostructure.

   Future direction: to investigate gate leakage mechanism, ALD-oxide and III-nitride heterostructures with mutually perturbed properties.

D. First demonstration of all binary n-channel AlN/GaN/AlN quantum well (GaN-on-Insulator) FETs. First demonstration of all binary p-channel GaN/AlN field effect transistors for complementary operation.

   Future direction: to improve AlN/GaN/AlN complementary FETs and understand their fundamental limits of operation in both 2D and 1D forms.

E. First demonstration of depletion-mode and enhancement-mode n-channel AlNGaN quantum wire (1D) FETs using top-down fabrication approach.

   Future direction: to demonstrate improved AlN/GaN/AlN quantum wire FINFETs.

The research findings have been partly documented in three Ph.D. dissertations [Yu Cao 2010, David Deen 2011 and Tian Fang 2012], 11 journal publications and 3 conference papers, which are listed below.

**Personnel supported**: (effective-full-time employees) 1.5 graduate student and 0.25 postdoctoral researchers.

**Equipment purchased:** none

**Dissertations (3):**

[1] Yu Cao, Ph.D. Dissertation: Study of AlN/GaN HEMTs: MBE growth, transport properties and device issues. Advisors: Debdeep Jena and Huili (Grace) Xing. University of Notre Dame, 2010.

[2] David Deen, Ph.D. Dissertation. Advanced designs of ultra-thin AlN/GaN HEMTs; A study of device design, modeling and analysis. Advisor: Huili (Grace) Xing. University of Notre Dame, 2011.

[3] Tian Fang, Ph.D. Dissertation: Carrier transport in graphene and GaN high electron mobility transistors. Advisors: Debdeep Jena and Huili (Grace) Xing. University of Notre Dame, 2012.

**Journal (11)/Conference (3) Publications:**

[1] Tom Zimmermann, Yu Cao, Jia Guo, Xiangning Luo, Debdeep Jena and Huili Xing. *Top-down AlN/GaN enhancement- and depletion- mode nanoribbon HEMTs.* Conference digest of 67th Device Research Conference, Penn State University, June 2009.

[2] Jia Guo, Tom Zimmermann, Debdeep Jena and Huili (Grace) Xing. *Ultra-scaled AlN/GaN enhancement- and depletion- mode nanoribbon HEMTs.* International Semiconductor Device Research Symposium (ISDRS), Dec. 2009.

[3] Chuanxin Lian, Yu Cao, Ronghua Wang, Guowang Li, Tom Zimmermann, Debdeep Jena and Huili Xing. *Molecular beam epitaxy regrowth of ohmics in metal-face AlN/GaN transistors.* International Conference on Compound Semiconductor Manufacturing Technology (Portland), April 2010.

[4] Yu Cao, Huili Xing, and Debdeep Jena. *Polarization-mediated remote surface roughness scattering in ultrathin barrier GaN high-electron mobility transistors. Appl. Phys. Lett.,* **97**, 222116 (2010).

[5] Yu Cao, Tom Zimmermann, Huili Grace Xing and Debdeep Jena. *Polarization-engineered removal of buffer leakage for GaN HEMTs. Appl. Phys. Lett., 96(4), 042102 (2010).*

[6] Guowang Li, Tom Zimmermann, Yu Cao, Chuanxin Lian, Xiu Xing, Ronghua Wang, Patrick Fay, Huili (Grace) Xing and Debdeep Jena. *Threshold voltage control in* $Al_{0.72}Ga_{0.28}N/AlN/GaN$ *HEMTs by work function engineering. IEEE Electron Dev. Lett., 31(9), 954, (2010).*

[7] Yu Cao, Kejia Wang, Guowang Li, Tom Kosel, Huili Xing, and Debdeep Jena. *MBE growth of high conductivity single and multiple AlN/GaN heterojunctions. J. Cryst. Growth*, 323(1), 529-533, (2011).

[8] Jia Guo, Yu Cao, Chuanxin Lian, Tom Zimmermann, Guowang Li, Jai Verma, Xiang Gao, Shiping Guo, Mark Wistey, Debdeep Jena and Huili (Grace) Xing. *Metal-face*

*InAlN/AlN/GaN high electron mobility transistors with regrown ohmic contacts by molecular beam epitaxy. Physica Status Solidi (a), 208(7), 1617-1619, (2011).*

[9] Debdeep Jena, John Simon, Kejia Wang, Yu Cao, Kevin Goodman, Jai Verma, Satyaki Ganguly, Guowang Li, K. Karda, Vladimir Protasenko, C. Lian, Tom Kosel, Patrick Fay, and Huili Xing. *Polarization engineering in group-III nitride heterostructures: New opportunities for device design. Phys. Stat. Solidi (a)*, 208(7), 1511-1516, (2011).

[10] Satyaki Ganguly, Jai Verma, Guowang Li, Tom Zimmermann, Huili Xing, Debdeep Jena. *Presence and origin of interface charges at atomic-layer deposited $Al_2O_3$/III-nitride heterojunctions. Appl. Phys. Lett., 99, 193504, 2011.*

[11] Jia Guo, Guowang Li, Faiza Faria, Yu Cao, Ronghua Wang, Jai Verma, Xiang Gao, Shipping Guo, Edward Beam, Andrew Ketterson, Michael Schuette, Paul Saunier, Mark Wistey, Debdeep Jena, Huili (Grace) Xing. *MBE regrown ohmics in InAlN HEMTs with a regrowth interface resistance of 0.05 ohm-mm. IEEE Elec. Dev. Lett., 33(4), 525-7, (2012).*

[12] Guowang Li, Ronghua Wang, Jia Guo, Jai Verma, Zongyang Hu, Yuanzheng Yue, Faiza Faria, Yu Cao, Michelle Kelly, Thomas Kosel, Huili (Grace) Xing, Debdeep Jena. *Ultra-thin body GaN-on-insulaor quantum well FETs with regrown ohmic contacts. IEEE EDL, 33, (2012).*

[13] Faiza Faria, Jia Guo, Pei Zhao, Guowang Li, Prem Kumar Kandaswamy, Mark Wistey, Huili (Grace) Xing, and Debdeep Jena. *Low resistance ohmic contacts to GaN with high Si doping concentrations grown by molecular beam epitaxy. Submitted, (2012).*

[14] Guowang Li, Ronghua Wang, Jai Verma, Yu Cao, Satyaki Ganguly, Amit Verma, Jia Guo, Thomas Kosel, Huili (Grace) Xing, Debdeep Jena. *Polarization-induced GaN-on-Insulator p-channel heterostructure FETs. Submitted, (2012).*